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Soil Organic Carbon Pools After 12 Years in No-Till Dryland Agroecosystems

L. A. Sherrod,* G. A. Peterson, D. G. Westfall, and L. R. Ahuja

ABSTRACT

Previous studies of no-till management in the Great Plains have shown that increased cropping intensity increased soil organic carbon (SOC). The objectives of this study were to (i) determine which soil C pools (active, slow, and passive) were impacted by cropping intensity after 12 yr of no-till across potential evapotranspiration (PET) and slope position gradients; (ii) relate C pool sizes to the levels found in total SOC; and (iii) determine C pool sizes relative to C levels found in a grass treatment (G). Cropping systems were wheat (*Triticum aestivum*)-fallow (WF), wheat-corn (*Zea mays* L.)-fallow (WCF), wheat-corn-millet (*Panicum miliaceum*)-fallow (WCMF), and continuous cropping (CC) at three PET sites in Colorado. Active C (Soil microbial biomass C [SMBC]); and slow pool C (particulate organic matter C; POM-C) increased as cropping intensity increased, dependent on PET. Passive C (mineral associated organic C [MAOC]) was strongly influenced by a site-by-slope position interaction but not by cropping system. Toeslope soils had 35% higher POM-C compared with summits and sideslopes. All C pools were strongly correlated with total SOC, with the variability decreasing as C pool turnover time increased. Carbon pool sizes in cropping systems relative to levels found in G were independently influenced by cropping system. The highest were found in the CC system, which had 91, 78, and 90% of the amounts of C found in the perennial G system in the active, slow, and passive C pools, respectively.

A KEY FACTOR in maintaining long-term production in the semiarid Great Plains is protection and/or improvement in the soil organic matter (SOM) content. Carbon inputs via crop production are influenced by factors such as climate and topography, as well as soil factors such as texture, structure, and fertility (Campbell et al., 1991; Lal et al., 1999). These factors set the production limits of a particular agroecosystem, and thus indirectly control soil C inputs.

Soil organic matter is not physically and biochemically homogeneous. To better understand the mechanisms by which C is lost or stored in terrestrial systems, SOC has been conceptually separated into various pools. Terrestrial ecosystem models have been employed to study the impacts of management and/or climate change on SOC turnover under different climates, topographies, and management. One example of a terrestrial model is CENTURY, which partitions SOC (Parton et al., 1988). Most of the organic C in soil (60–70%) resides in the passive pool, with turnover times ranging from centuries to millennia. Approximately 20 to 40% of SOC is in the slow pool, with decadal turnover times, while <5% of the SOC is found in the rapidly cycling active fraction, with turnover times ranging from hours to months (Follett, 2001; Shaffer et al., 2001; Burke et al., 1997; Parton et al., 1988). The POM-C fraction has been reported to estimate the slow turnover pool (Cambardella and Elliott, 1992), while methods that assess microbially respired CO_2–C estimate the active fraction of SOC (Davidson et al., 1987; Franzluebbers et al., 1996, 2000). Carbon mineralized (C_{MIN}) after rewetting air-dry soil during a 3-d incubation has been correlated with SMBC, explaining 86% of the variability (Franzluebbers et al. 1996, 2000).

Climate and soil texture strongly influence the dynamics of SOM with C losses due to cultivation increasing with precipitation and decreasing with soil clay content (Burke et al., 1989). Predicted Great Plains regional patterns in SOC show higher levels in the cooler Northern Great Plains and lower in the warmer Southeast Great Plains (Burke et al., 1989, 1995). Analysis of climatic and textural controls on SOC by Parton et al. (1987) indicate that temperature is a direct control on SOC decomposition, while soil texture controls both the formation and decomposition rates of the active and slow SOC pools. Hook and Burke (2000) suggest that soil texture has a major impact over the biogeochemical processes, which is a reason why topographic influences are observed in SOC pools.

Besides the limits imposed by climate, topography, and soil texture, the particular management system also has a major impact on the quantity and quality of SOC found within an agroecosystem. In dry regions such as the Great Plains, conversion to no-till management has increased SOM in surface soils with the most dramatic effects occurring in cropping systems without summer fallow (Campbell and Zentner, 1993; Bremer et al., 1995; Potter et al., 1998; Bowman et al., 1999; Campbell et al., 2000; Sherrod et al., 2003). Publications that report responses in SOC pools to management changes across cropping system intensity gradients, soils, and climate are few in number. This paper reports data from a study initiated in 1985 in eastern Colorado to evaluate the effects of cropping intensity on production, water-use efficiency, and soil physical and chemical properties across PET and topographic gradients. A number of publications have reported the effects of cropping intensity, slope position, and PET gradient on soil C and N properties. Wood et al. (1990) reported a 61% increase in C_{MIN} during a 30-d incubation (surface 0 to 5 cm of

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Abbreviations: CC, continuous cropping; C_{MIN}, carbon mineralized; CRP, Conservation Reserve Program; G, grass; LSD, least significant difference; MAOC, mineral-associated organic carbon; MAT, mean annual temperature; OPE, open pan evaporation; PET, potential evapotranspiration; POM-C; particulate organic matter carbon; SMBC, soil microbial biomass C; SOC, soil organic carbon; SOM, soil organic matter; WCF, wheat–corn–fallow; WCMF, wheat–corn–millet–fallow; WF, wheat–fallow.

soil) in the WCMF system compared with the WF system, with the toeslope soils having a higher C_{MIN} than the summit or sideslope soils just 3.5 yr after a change in management. In addition, Wood et al. (1991) found after 4 yr under no-till that SOC and total N levels accumulated, maintained, and declined in the 0- to 2.5-, 2.5- to 5-, and 5- to 10-cm soil depths, respectively, for all cropping systems studied. Ortega et al. (2002), investigating the WF and WCMF treatments on summit soils across the PET gradient after 8 yr, found that SOC and soil organic N contents were directly related to the amount of plant residue present in each layer. Shaver et al. (2002), 12 yr after initiation, found that macroaggregates made up a higher percentage of total aggregates in the CC and WCF systems than in WF. Increases in the amount of macroaggregation were linearly related ($R^2 = 0.89$) to the SOC content of the aggregates (Shaver et al., 2003). At the end of 12 yr, Sherrod et al. (2003) reported that annualized stover inputs (averaged over phases of multiple year rotations) explained 80% of the variability in total SOC and total N contents in the surface 0- to 10-cm soil depth. Slope position and PET gradient effects on SOC and total N contents were found to be independent of cropping system. In addition, CC without summer fallow significantly increased both SOC and total N in the 0- to 2.5-, 2.5- to 5-, and 0- to 10-cm soil depths relative to the WF system (Sherrod et al., 2003).

Active, slow, and passive SOC pools play various functional roles in SOM dynamics and nutrient cycling. Biological transformations among C pools are influenced by soil factors such as temperature, texture, and water content (Scharpenseel et al., 1992). Therefore the responses to management change across PET and slope gradients are likely to vary depending on the C pool. This paper evaluates the effects of cropping systems (intensity gradient) over slope positions (productivity gradient) across a PET gradient on soil C pools to a soil depth of 10 cm. We attempted to quantify which C pools were impacted by the increased biomass additions that resulted from cropping intensification after a change in management from conventional tillage crop-fallow to a water conserving no-till system.

This study builds on the findings of Sherrod et al. (2003) by measuring which SOC pools (active, slow, and passive) have been impacted by cropping intensity and interactions with slope position and PET gradient. We hypothesized that the SOC gains resulting from increased cropping intensity (Sherrod et al., 2003) were largely due to increases in the active and slow SOC pools and that the passive SOC pool would not be impacted by cropping intensity during the 12-yr time-span. The active and slow C pools represent the biologically active pools that are largely responsible for nutrient cycling, improved soil structure, and water infiltration, all of which enhance production. The passive C pool was expected to be influenced by soil textural differences that are found across PET sites and slope positions because clay content has been associated with the formation of SOM in the passive C pool (Parton et al., 1993). We also hypothesized that the response of SOC pools to cropping intensity would be modified by the PET and soil gradients because available soil water, and thus production and decomposition are linked to them. Depositional soils at the low and medium PET sites have the highest SOC and total N (Wood et al., 1991; Sherrod et al., 2003). In addition the relative proportion of these C pools should change with increases in the biologically active pools (active and slow) and decreases in the recalcitrant (passive) C pool as cropping intensity increases. Our objectives were to (i) determine which soil C pools (active, slow, and passive) were impacted by cropping intensity at the end of 12 yr of no-till management across PET and topographic gradients; (ii) relate both the absolute and relative C pool sizes to the levels found in total SOC; (iii) determine the C pool sizes relative to the levels found in a perennial G treatment as an estimate of how well cropping systems are doing to that of a system that simulates the maximum levels obtainable over this 12-yr time-span.

MATERIALS AND METHODS

Site (PET Gradient), Topographic Gradient, and Cropping Systems

This study was conducted within a long-term sustainable dryland agroecosystems management project, that was initiated in 1985 in eastern Colorado to evaluate the effects of cropping intensity on production, water-use efficiency, and other selected soil chemical and physical properties (Peterson et al., 1993). This experiment has three major variables, (i) PET gradient, (ii) topography (slope position), and (iii) cropping intensity under no-till management. This particular C investigation was made 12 yr after initiation of the experiment. Soils at each site had been under conventional tillage crop-fallow management for over 50 yr before the initiation of this study in 1985.

The three sites represent an increasing PET gradient from north to south, but all have a long-term mean annual precipitation of 420 mm (Table 1). The northern site at Sterling (40°

Table 1. Elevation, mean annual temperature, mean annual precipitation, and selected climatic properties of the research sites in eastern Colorado.

Site	Elevation	MAT†	MAP‡	Days above 32°C	OPE§	Deficit water¶	Relative PET#
	m	°C	mm	d	mm	mm	
Sterling	1341	9.3	440	42	1600	−1160	Low
Stratton	1335	10.8	415	54	1725	−1310	Medium
Walsh	1134	12.2	395	64	1975	−1580	High

† MAT = mean annual temperature.
‡ MAP = mean annual precipitation from 1961–1990.
§ OPE = open pan evaporation during the growing season.
¶ Deficit water = precipitation − open pan evaporation.
# PET = potential evapotranspiration.

Table 2. Soil texture, bulk density, and classification in the 0- to 10-cm depth at Sterling, Stratton, and Walsh sites.†

Site	Catena position	Sand	Silt	Clay	Bulk density	Pedon	Classification
		%			g cm^{-3}		
Sterling	Summit	37	36	27	1.49	Weld	Fine-silty, mixed, mesic Aridic Argiustoll
	Side	39	34	27	1.35	Satanta	Fine-loamy, mixed, mesic Aridic Argiustoll
	Toe	30	43	27	1.30	Albinas	Fine-loamy, mixed, mesic Pachic Argiustoll
Stratton	Summit	20	45	35	1.44	Norka	Fine-silty, mixed, mesic Aridic Argiustoll
	Side	30	45	25	1.35	Richfield	Fine, montmorillonitic, mesic Aridic Argiustoll
	Toe	22	45	33	1.24	Kuma	Fine-silty, mixed, mesic Pachic Argiustoll
Walsh	Summit	66	15	19	1.59	undefined	Fine-loamy, mixed mesic, Aridic Ustochrept
	Side	50	25	25	1.49	undefined	Fine, montmorillonitic, mesic, Ustollic Haplargids
	Toe	35	36	29	1.42	Nunn	Fine, montmorillonitic, mesic Aridic Argiustoll

† Adapted from Sherrod et al. (2003); Peterson et al. (1993); and Wood et al. (1991).

22′12″ N lat., 103°7′48″ W long.) has a water deficit (precipitation–open pan evaporation [OPE]) of 1140 mm yr^{-1}. The medium site at Stratton (39°10′48″ N lat., 102°15′36″ W long.) has a water deficit of 1290 mm yr^{-1}. The southern site is at Walsh (37°13′48″ N lat., 102°10′12″ W long.) with water deficit of 1555 mm yr^{-1}. The Sterling and Stratton sites represent approximately 73 and 83% of the relative PET respectively compared with the Walsh site (Peterson et al., 1998). The relative PET gradient is represented as low, medium, and high for Sterling, Stratton, and Walsh sites, respectively.

The topographic variable is represented by slope positions of summit, side, and toeslope along a catenary sequence. Soil classification, texture, and soil bulk density characteristics are presented in Table 2. Each slope position represents a unique soil series common to the geographic area, which represents nine different soil series across the three sites (Peterson et al., 1993).

Cropping systems representing a gradient of cropping intensities were placed across the soil sequences at each site in strips that were 6.1 m wide by 185 to 300 m long, depending on site. All phases (entry points) of each cropping system are present at each site every year accounting for a total of 11 treatments including a perennial native G treatment. For example, WF cropping system requires two experimental units; one for wheat–fallow and the other for fallow–wheat in each of the two field replications. Cropping systems are: wheat–fallow (WF), wheat–corn–fallow (WCF), wheat–corn–millet–fallow (WCMF), and continuous cropping (CC), which included corn/sorghum [*Sorghum bicolor* (L.) Moench], wheat, hay millet, and sunflower *(Helianthus annuus)* in order of frequency. The cropping system gradient is as follows: WF has an intensity factor of 0.50 (crops divided by year in the rotation) and WCF, WCMF, and CC are 0.67, 0.75, and 1.0, respectively.

Grain sorghum was grown in place of corn in the cropping systems at Stratton before 1990. Grain sorghum production at Stratton was limited by growing season length (Peterson et al., 1991), and was thus replaced by corn in 1990 at this location. Sorghum was grown at Walsh, because of its suitability to high ET and longer growing season. Crops were planted using no-till planters and drills that only disturbed the soil in a narrow band to allow for a seed row. Fertilizer N (32-0-0) and P (10-34-0) were applied based on annual soil tests for available N and P.

A perennial grass treatment (G) also was established in the spring of 1986 with a seed mixture containing equal seed numbers of crested wheatgrass [*Agropyron cristatum* (L.) Gaertn.], western wheatgrass (*Agropyron smithii* Rydb.), sideoats grama [*Bouteloua curtipendula* (Michx.) Torr.], little bluestem [*Schizachyrium scoparium* (Michx.) Nash], blue grama [*Bouteloua gracilis* (H.B.K.) Lag. ex Steud.], and buffalograss (*Buchloe dactyloides*). Annual removal of the grass biomass was initiated in the fall of 1990. Because it is a perennial system, the G treatment serves as an estimate of maximum underground organic C additions and serves as a simulation of a Conservation Reserve Program (CRP) treatment (Reeder et al., 1998). Statistical analyses do not include this treatment because it is not a part of the cropping intensity gradient.

Stover yields were determined by collecting two biomass samples from a 0.50-m square area at each site, slope, and cropping system each year. Total aboveground biomass was weighed in the laboratory and the stover was separated from the grain and weighed to get a stover/grain ratio. Field combine yields corrected for grain moisture were divided by the stover/grain ratio to estimate stover yields from each site, slope, and cropping system each year. Stover yields collected over 12 yr at each experimental unit for two replications therefore represents a collective $n = 108$, 144, 162, and 216 for the WF, WCF, WCMF, and CC cropping systems, respectively. These data were annualized by adding up the annual stover inputs for the multiple year treatments starting out in wheat in the fall of 1985 and the CC treatment and divided by 12 within each site, slope, cropping system, and replication ($n = 72$).

Sample Preparation and Analysis

Soil cores were taken to 10-cm depth from the fallow phase of the WF, WCF, and WCMF cropping systems and the CC and G treatments at all three sites and at all three slopes in the fall of 1997. Cores were partitioned into 0- to 2.5-, 2.5- to 5-, and 5- to 10-cm depth increments. Fifteen 2.54-cm diam. soil cores were obtained from each treatment combination and composited by depth. All visible plant material (roots, stems, or leaves) larger than 2 mm was removed and surface residue also was excluded from the samples. Soils were air dried and ground to pass a 2-mm sieve. A subsample of 20 to 25 g was powder ground with a steel ball-mill grinder to pass through a 180-mm (80-mesh) sieve and analyzed for total C with dry combustion using a Leco CHN-1000 auto analyzer (Leco, St. Joseph, MI) from a 0.2-g subsample. Carbonates were determined by using a modified pressure calcimeter method (Sherrod et al., 2002), and inorganic C was then subtracted from total C by dry combustion for determination of SOC. Two bulk density measurements were made per experimental unit at the time of soil sampling using a 5.36-cm diam. double-cylinder core sampler in 0- to 2.5-, 2.5- to 5-, and 5- to 10-cm depth increments (Grossmand and Reinsch, 2002). The average of the two bulk density numbers were used to calculate soil C mass for the various pools (Table 2). Carbon concentrations were converted to mass using the following formula:

$$\text{kg ha}^{-1} = \mu\text{g C g}^{-1} \times \text{g soil cm}^{-3} \times \text{(depth increment in cm/10)}$$

Each depth increment mass for all C fractions was then summed for a depth of 10 cm.

Soil Microbial Biomass Carbon

Composited samples of the 2-mm sieved soils of the 0- to 2.5- and 2.5- to 5-cm soil depth were analyzed for respired CO_2 by incubating 20-g soil samples in 1-L canning jars at 30°C and 50% water-filled pore space for 3 d. Total soil pore space percentage was used to estimate amount of water needed to obtain 50% water-filled pore space. Pore space percentage was calculated by weighing soil samples into 45-mm Wheaton snap cap jars with a line marked for a bulk density of 1.00 and using a standard particle density of 2.65 g cm^{-3}. Alkalai base traps were titrated at 3 d to determine quantity of CO_2–C evolved (Anderson, 1982; Franzluebbers et al., 1996). Due to equipment availability, subsurface soil samples of 5 to 10 cm were analyzed for respired CO_2 by a slightly different method. Subsurface samples were aerobically incubated at 30°C and 50% water filled pore space in a 500-mL Wheaton serum bottle with a rubber septum and aluminum sealing ring. Respired CO_2 during 3 d was determined from headspace gas with a 1-mL syringe and analyzed by a LI-COR CO_2 gas analyzer (Li-Cor, Lincoln, NE) using compressed N as a carrier gas (Davidson et al., 1987). An artificial bulk density value of 1.0 was obtained by tapping soils within a known volume within the incubation chambers. Regression analysis of CO_2 determined by titration compared with the LI-COR CO_2 gas analyzer ($n = 10$) confirmed similar results with a slope of 0.98 and an $R^2 = 95$ (data not shown). Mineralized CO_2–C concentrations were added for the two depth increments and then converted to SMBC by using an equation developed by Franzluebbers et al. (2000) in which the flush of CO_2 from rewetting air-dried soils obtained from 20 soil series containing a wide range of organic C ($n = 399$) explained 86% of the variability in SMBC. Concentrations were then converted to a mass bases using field bulk density values. The equation used is as follows:

Soil microbial biomass C

$$y = 337 + 2.4x$$

Particulate Organic Matter Carbon and Mineral Associated Organic Carbon

The POM-C was determined by dispersing a 10-g subsample with 40-mL of sodium hexametaphosphate (5 g L^{-1}) and shaking on a reciprocating shaker overnight (Gregorich and Ellert, 1993; Cambardella and Elliott, 1992). The soil suspension was then poured over a 53-μm screen and all the material passing through this screen (silt and clay) was retained and dried overnight at 70°C. The soil passing through the sieve, as well as a separate subsample of whole soil (2-mm sieved), were powdered with a ball mill grinder to pass a 80-μm sieve. Both powdered samples were analyzed for total C on a Leco-CHN 1000 combustion furnace analyzer (Nelson and Sommers, 1982). Inorganic C was measured in the total SOC and the $<$53-μm fraction using a modified pressure calcimeter method (Sherrod et al., 2002), and organic C was calculated as total C from dry combustion minus inorganic C. The organic C associated with the silt- and clay-size fraction ($<$53 μm) is termed mineral-associated organic C (MAOC). Particulate organic matter C was then calculated as the difference between total whole SOC and MAOC.

Experimental Design and Statistical Analysis

The experimental design was a split-split block that included three sites representing a PET gradient, three topographic (slope) positions, and four levels of cropping intensity. Each phase of each cropping system was randomly imposed at each location in strips across slopes within each of the two replications at each site (Peterson et al., 1993). The experimental unit therefore is a specific soil position within a site and phase within a cropping system. The variance was partitioned to test effects and interactions using analysis of variance with the general linear model of the Statistical Analysis System (SAS Inst., 1999) using the appropriate error term. Main effect mean separations were determined with Fisher's Protected least significant difference (LSD) when the overall model was significant ($P < 0.05$). Site was tested with replication (site) term. Slope position and site-by-slope interaction was tested using a slope × replication (site) term. Cropping intensity and site-by-cropping were tested using the cropping × replication (site) term. When interactions were significant, LSD's were calculated by comparing slopes within sites (site × slope), cropping system within site (site × cropping), cropping system within and slope (slope × cropping), and cropping system within site and slope (site × slope × cropping) using the appropriate standard error term. Correlation and regression analyses were performed in SAS (SAS Inst., 1999).

RESULTS AND DISCUSSION

Cropping Intensity

The primary hypothesis for this study was that the SOC gains resulting from increased cropping intensity (Sherrod et al., 2003) could be accounted for by increases in the active and slow C pools as estimated by SMBC and POM-C, respectively. We further hypothesized that the response of SOC pools to cropping intensity would be modified by the PET and soil gradients because available soil water, and thus production and decomposition are closely linked to them. Furthermore we expected that the passive SOC pool, as estimated by MAOC, would not be impacted by cropping intensity during the 12-yr time-span.

We knew that increased cropping intensification had increased total SOC and total N in the 0- to 10-cm soil depth independent of slope position and PET site (Sherrod et al., 2003) and that stover production accounted for 80% of the variability. Twelve years after initiation of the experiment we found cropping intensification had a major effect on SMBC but the effect was modified by the PET gradient-by-cropping system interaction (Table 3). The interaction occurred because there was no change in the levels of SMBC due to cropping systems at the high PET site. The overall trend across sites was for increased SMBC with increasing cropping intensity. At the low and medium PET sites, the CC system had significantly higher SMBC than the WF and WCF systems.

The size of the slow C pool, as estimated by POM-C, was also strongly influenced by cropping intensity with a P value = 0.0001 (Table 3). As with the rapid turnover pool, this affect was modified by the PET gradient. A site-by-cropping intensity interaction occurred because POM-C did not increase uniformly at each site as cropping systems intensified. Particulate organic matter C levels were highest in the CC cropping system at all sites compared with WF, but the highest PET site (Walsh) had approximately a third of the levels found

Table 3. Soil microbial biomass C (SMBC), particulate organic matter C (POM-C), and mineral associated organic C in the 0- to 10-cm soil depth as affected by PET gradient, cropping intensity, and slope position after 12 yr under no-till management.

SITE (PET Gradient)	Cropping intensity				Soil slope position		
	WF†	WCF‡	WCMF§	CC¶	Summit	Side	Toe
	kg ha^{-1}						
	SMBC						
Sterling (Low PET)	690 b*	795 b*	785 b*	1175 a*	915 a**	810 b**	855 b**
Stratton (Medium PET)	785 b*	820 b*	935 ab*	995 a*	990 a**	720 b**	945 a**
Walsh PET (High PET)	520 a	640 a*	590 a*	600 a*	540 b**	540 b**	685 a**
	POM-C						
Sterling (Low PET)	3000 b*	3780 b*	3380 b*	5735 a*	3320 a	4040 a	4 560 a
Stratton (Medium PET)	3510 b*	4650 a*	4980 a*	5160 a*	4125 a	3115 a	6 490 a
Walsh PET (High PET)	1185 b*	1525 ab*	1905 ab*	2270 a*	1495 a	1280 a	2 390 a
	MAOC						
Sterling (Low PET)	9275 a	9550 a	9520 a	9795 a	9760 a***	8850 b***	9 995 a***
Stratton (Medium PET)	9740 a	9670 a	9840 a	9985 a	9545 b***	8090 c***	11 790 a***
Walsh (High PET)	4655 a	5380 a	5355 a	5330 a	3275 c***	4280 b***	7 990 a***

* Significant at $P < 0.05$.
** Significant at $P < 0.01$.
*** Significant at $P < 0.001$.
† Wheat (*Triticum aestivum*)-fallow.
‡ Wheat-corn (*Zea mays*) or sorghum [Sorghum bicolor (L.) Moench]-fallow.
§ Wheat-corn or sorghum-millet (*Panicum miliaceum*)-fallow.
¶ Continuous cropping systems. Comparisons were made on the basis of analysis of variance (ANOVA) and LSDs determined at the 0.05 alpha level within a site across cropping intensity or within a site across slope position. Means followed by the same letter within a row are not significantly different.

at the other two sites. This can be explained in part by an approximately 30% lower average production at this site over the 12-yr cropping history (Peterson et al., 1998). In contrast to the active C pool at the Walsh site, the slow C pool did increase with cropping intensity. Similar trends were found in the medium PET site with the highest POM-C levels found in the most intensive system (CC) and the lowest levels found in the WF system. It is of interest that the SMBC and POM-C fractions show similar interactions as POM-C is a major substrate used by microorganisms.

As hypothesized the passive C pool (MAOC) was not influenced by cropping intensity (Table 3). Significant changes in this large SOC pool (70% of total SOC) would likely take decades to see. Hook and Burke (2000) working in a shortgrass landscape in Colorado showed that neither the presence nor absence of plants affected the MAOC pool.

Potential Evapotranspiration Gradient and Slope Position Effects

Sherrod et al. (2003) reported that total soil C and N contents at the low and mid points on the PET gradient, Sterling and Stratton, were approximately double the amounts found at the site with the highest PET (Walsh). Toeslope soils were approximately 30% higher in total C and N than summit and sideslope soils in the 0- to 10-cm depth. As might be expected, in this study we found the smallest C pools at the site with the highest PET (Walsh), and the largest slow and passive C pools were found in the toeslope soils (Table 3). The magnitude of the active and passive C pools was influenced by PET gradient, and the interactive effect of cropping system and/or slope position (Table 3). As expected, the highest PET site (Walsh) had approximately 50% lower slow and passive C levels than did the medium and low PET points on the gradient as hypothesized. Walsh also has the highest sand contents with 66, 50, and 35% for summit, side, and toeslope positions, respectively (Table 2). The active C pool was affected by a site-by-slope interaction. Comparing slope positions within a site, only the toeslope at Walsh had a significantly higher active C pool, (685 kg ha^{-1}) compared with summit and sideslopes (540 kg ha^{-1}); no clear slope affect was observed at the low and medium PET sites. The slow C pool (POM-C) was not affected by PET site ($P = 0.08$) at the established $\alpha = 0.05$, but the trend was for decreased levels at the high PET site. The strongest influence climate had (PET site) was found in the PET site-by-slope position interaction ($P = 0.0005$) with the passive C pool estimated by MAOC. This interaction represents the intrinsic SOC levels developed within the PET site-specific parent material and topography of the respective soil (Table 3). At Stratton, the medium PET site, C pool levels varied along the catena in the expected manner, with the lowest levels found on the sideslope and the highest levels found on the toeslope (Table 3). The size of the passive pool at Sterling (lowest PET site) did not differ between the summit and toeslope soils. However, toeslopes did have the highest levels at both the medium and high PET sites. The slow C pool, as represented by POM-C, was affected by slope with toeslope soils having 35% more POM-C than summit and sideslope soils (Fig. 1). Production is generally highest on toeslope soils therefore this relationship was to be expected due to the direct linkage between stover inputs and the slow C pool, which is consistent with the findings of other research done in the Great Plains Region (Aguilar et al., 1988; Burke et al., 1995).

Both the active and slow C pools were affected by PET site and/or slope position interactions, which shows the strong influence that texture has on production and therefore on SOM quantity and quality. Soil texture differences within and across sites directly impact waterholding capacity, which strongly influence production

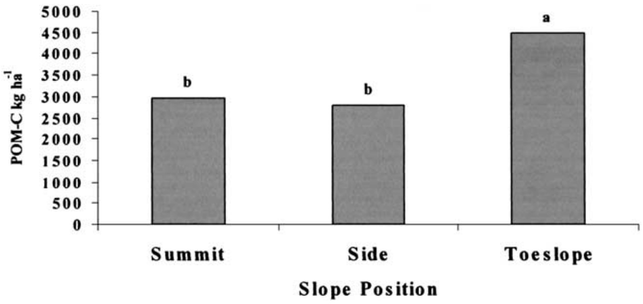

Fig. 1. Particulate organic matter C (POM-C) in the 0- to 10-cm depth. Means followed by a different letter are statistically different ($P < 0.05$) using Fisher's LSD.

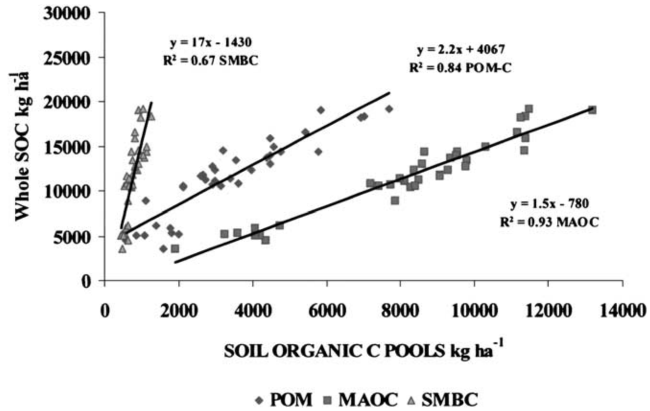

Fig. 2. Relationships of soil microbial biomass C (SMBC), particulate organic matter C (POM-C), and mineral-associated organic C (MAOC), in the 0- to 10-cm soil depth to whole soil organic C (SOC) after 12 yr in no-till management averaged across PET sites, slope positions, and cropping systems.

in dryland systems. Needelman et al. (1999), working in Illinois found that the slow C pool did not increase after conversion from a tillage system to a no-till system in sandy soils compared with finer textured soils. We found similar results, with the Walsh site having approximately a third the levels of the slow C pool compared with the low and medium PET sites with finer textures. It is unclear as to what extent PET gradient is affecting C pool sizes, relative to soil texture differences, both of which affect available soil water, which is the production control in the Great Plains.

Correlation and Regression Analysis

Our second objective was to evaluate the absolute and relative size levels of the C pools to the whole SOC. A correlation matrix of the mass of active, slow, and passive C pools, compared with SOC, and annualized stover production is presented in Table 4. These correlations permit evaluation of the relationships of active, slow, and passive to the total SOC in addition to relationships within the C pools. The active C pool, represented by SMBC, had a $r = 0.82$ and the regression relationship with whole SOC explained 67% of the variability (Fig. 2). This regression indicates that small changes in the active C pool would provide large increases in the whole SOC. The slow turnover C pool represented by POM-C also was strongly correlated to whole SOC ($r = 0.91$) (Table 4). The regression of POM-C and whole SOC (Fig. 2) captures the variability across the PET gradient, soils (slope position), and cropping intensity and shows that 84% of the variability in total SOC was explained by the POM-C fraction. This demonstrates the robust nature of using POM-C as an indicator for changes in total SOC. Wander and Bollero (1999) identified POM as a promising soil quality measure. Franzluebbers and Arshad (1997) working in Alberta and British Columbia, Canada found POM-C was more sensitive to tillage induced changes in SOC than was total SOC. The strongest correlation observed existed between total SOC and passive C (mineral-associated organic C) with $r = 0.96$. This correlation represents the edaphic factors that strongly influence biomass production, such as water holding capacity, soil texture, structure, and overall controls on SOM quality through aggregation, namely size of silt and clay fraction. A strong relationship would be expected with the passive C pool based on the absolute magnitude of this pool to the whole SOC pool in addition to the highly stable composition of this fraction. The regression of the passive C pool with SOC accounted for 93% of the variability associated with SOC (Fig. 2). The slope from this regression indicates that approximated 67% of the total SOC is in the passive C pool over all PET sites, slope positions, and cropping systems. However, this pool is not responsive to management-induced changes in SOM. The regression's shown in Fig. 2 show increasing variability going from the non-labile to the moderately labile to the labile C pools as represented by MAOC, POM-C, and SMBC, respectively, as would be expected due to the size and relative stability of the respective fractions.

Table 4. Correlation matrix (values below the diagonal) and significance ($P > r$), values above the diagonal in italic) in the 0- to 10-cm depth averaged over PET gradient, soil position and cropping intensity, and slope position after 12 yr under no-till management.

	C POOL	STOVER†	SOC‡	SMBC§	POM-C¶	MAOC#
			Total	Active	Slow	Passive
STOVER		–	*<.0001*	*<.0001*	*<.0001*	*<.0001*
SOC	**Total**	**0.8674**	–	*<.0001*	*<.0001*	*<.0001*
SMBC	**Active**	**0.7748**	**0.8189**	–	*<.0001*	*<.0001*
POM-C	**Slow**	**0.8872**	**0.9142**	**0.8062**	–	*<.0001*
MAOC	**Passive**	**0.7760**	**0.9639**	**0.7555**	**0.7739**	–

† Stover = annualized stover.
‡ SOC = soil organic C.
§ SMBC = soil microbial biomass C.
¶ POM-C = particulate organic matter C collected between a 2-mm sieve and a 53-um sieve.
# MSOC = mineral associated organic C collected below a 53-um sieve in POM analysis.

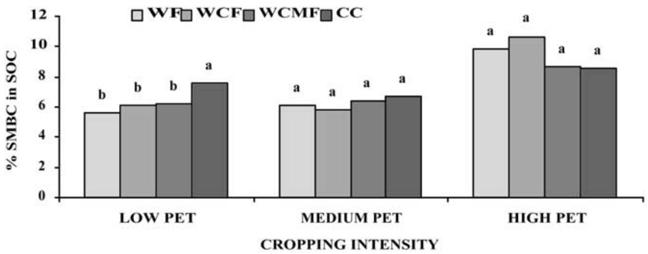

Fig. 3. Interaction of potential evapotranspiration (PET) and cropping intensity on the percent of soil microbial biomass carbon (SMBC) found in soil organic carbon (SOC) in the 0- to 10-cm soil depth after 12 yr under no-till management. Means followed by a different letter are statistically different ($P < 0.05$) using Fisher's LSD.

Annualized stover production was strongly correlated with all C pools as well as whole SOC as would be expected. The strongest correlation was found with the slow C pool (POM-C) with a $r = 0.89$ (Table 4). This reflects the strong linkage of C inputs into the system with changes in the POM-C fraction. Alvarez and Alvarez (2000) working with a grassland vs. cropping systems under plow and no-till management found 88, 77, and 78% of the variability explained when biomass C was correlated with respired C, light fraction C, and total C, respectively. We found that 60, 79, and 79% of the variability associated with SMBC, POM-C, and SOC respectively, was accounted for by the annualized stover production.

Relative C Pool Size To SOC

Relative SOM quality can be evaluated by the collective association of C pool sizes. We expect that increases in production (cropping intensification) that increase C inputs back into the system will change the relative C pool sizes by increasing the levels found in the biologically active pools (active and slow) while simultaneously reducing the size of the passive C pool. Since available water is the key control on C pool size in the semiarid Great Plains, soil factors such as soil texture and slope position and the climatic factor of PET should have a direct impact on C pools. The response in relative C pool size to management change across differences in PET gradient and slope positions also would be expected to vary. The active C pool was influenced by cropping system although not independent of PET site. We expect that increased cropping intensity would cause the largest changes in C pool sizes at the sites with the lowest PET. The lowest PET site did have a significant increase in the pool size of the active C relative to SOC for the CC system (no summer fallow) compared with the other cropping systems (Fig. 3). No differences in the relative active C pool size were found at the medium and high PET sites.

The slow (POM-C) and the passive (MAOC) C pools were both influenced by multiple interactions of PET gradient, slope position, and cropping system. The reason for these interactions is unclear, and they do not have apparent biological explanations. In general, 31, 29, and 25% of the SOC was found in the slow C pool at the medium, low, and high PET sites, respectively.

The relative pool sizes as a percentage of the total SOC within a given cropping intensity are presented in Table 5. The percentage of the total SOC represented by the active and slow C tended to increase with increasing cropping intensity. Active, slow, and passive C pools, as a percentage of total SOC, averaged across cropping intensity was 7, 28, and 71% of total SOC, similar to conceptional pool sizes described by the CENTURY model (Parton et al., 1987).

Relative Carbon Pool Size to a Perennial Grass Treatment

Continuous G systems are known to store larger quantities of soil C than annual cropping systems because of their perennial nature and their extensive root systems. Thus grass systems represent the maximum potential C storage potential in our ecosystem. Since our experiment included a perennial grass treatment we were able to compare the pool sizes found in each cropping system to that found in the perennial G treatment. The proportion of soil C found in the active, slow, and passive C pools, relative to these same pools in the G treatment

Table 5. Soil C fraction size relative to the whole soil C and relative to C in the perennial grass (G) treatment in the 0- to 10-cm depth as affected by cropping intensity of wheat-fallow (WF), wheat-corn-fallow (WCF), wheat-corn-millet-fallow (WCMF), and continuous cropping (CC) after 12 yr in no-till management averaged over PET sites and slope positions.

Turnover	ACTIVE		SLOW		PASSIVE	
	SMBC†		POM-C‡		MAOC§	
Cropping Intensity	% of SMBC in SOC	% SMBC found in G	% of POM-C in SOC	% of POM-C found in G	% MAOC in SOC	% of MAOC found in G
	%					
WF	7.2	60 c#	25	44 c	75	66 b
WCF	7.5	70 b	27	59 b	73	84 a
WCMF	7.1	72 b	28	60 b	71	81 a
CC	7.6	91 a	33	78 a	67	90 a
G	10.8	100	40.0	100	60	100
	P-value					
	0.2786	0.0083	0.0247	0.0003	0.0247	0.0195

† SMBC = soil microbial biomass C.
‡ POM-C = particulate organic matter carbon (size fraction between 2 mm and 53 um).
§ MAOC = mineral-associated organic carbon of silt and clay size that passes through 53-um sieve size.
# Comparisons were made on the basis of analysis of variance (ANOVA) and LSD's determined when interactions were not present with PET site and slope position. Means followed by a different letter within the same column are significantly different ($P < 0.05$) using Fisher's LSD.

are presented in Table 5. An analysis of variance of these data showed that cropping system effects were independent of PET site and slope position for all pools. The CC system, with no summer fallow compared best with the G system. Increases in cropping system intensity caused all soil C pools to increase relative to perennial G. It was surprising that the passive C pool, as represented by MAOC, was also influenced by cropping intensity.

These data suggest that moving to cropping systems with more annual cropping and fewer summer fallow periods will increase soil C in all pools to levels more nearly like perennial G systems. It is encouraging that these changes occurred over a relatively short period of time (12 yr). Note that complete elimination of summer fallow with the CC has resulted in 91, 78, and 90% of the active, slow, and passive C pool levels, respectively, that were attained by growing perennial grasses similar to CRP.

CONCLUSIONS

Management systems have a major influence on the total SOC as well as the relative distribution of the various C pools that reside within it. Regions such as the Central Great Plains are vulnerable to soil C loss due to relatively low precipitation, high PET, and high soil erosion potential. To increase production in these regions, special care must be taken to maximize the efficiency of the precipitation received. By implementing no-till management in regions and soil types that are conducive to cropping intensification, production increases may be achieved (Peterson et al., 1996; Bowman et al., 1999; Ortega et al., 2002). We have shown that cropping intensity, most notably the CC system, increased active and slow C pools in a 0- to 10-cm depth 12 yr from conversion from a tillage crop-fallow to a no-till cropping intensification system. These increases are due to primarily increases in the slow fraction. We have shown that as cropping intensity increased, so did the levels of the biologically active C pools (active and slow) as a relative size of the C pool found in a G treatment. The impact of cropping intensification in this case was independent of PET gradient and topography (slope position).

Management systems, which add diversity to the relative distribution of C pool sizes enhance SOM quality and quantity. Diversity in soil C pools is achieved by increases in the size of the biologically active pools that have direct implications on production by increasing soil water capture, reducing erosion potential, increasing nutrient supplying capacity, structure, aggregation, and tilth in addition to being sensitive to management induced changes in SOM (Elliott et al., 1994; Wander et al., 1994). Cropping systems that reduced or eliminated summer fallow show the greatest positive impact on these biologically active pools in the Central Great Plains. By adding diversity to the system by diversifying the cropping system thereby greatly reducing the fallow time, intensified crop production through no-till management in this region can provide diversity in SOC pools, which are more similar to a native system.

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REFERENCES

Aguliar, R., E.F. Kelly, and R.D. Heil. 1988. Effects of cultivation on soils in Northern Great Plains rangeland. Soil Sci. Soc. Am. J. 52:1081–1085.

Alvarez, R., and C.R. Alvarez. 2000. Soil organic matter pools and their associations with carbon mineralization kinetics. Soil Sci. Soc. Am. J. 64:184–189.

Anderson, J.P.E. 1982. Soil respiration. p. 831–871. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Bowman, R.A., M.F. Vigil, D.C. Nielsen, and R.L. Anderson. 1999. Soil organic matter changes in intensively cropped dryland systems. Soil Sci. Soc. Am. J. 63:186–191.

Bremer, E., B.H. Ellert, and H.H. Jansen. 1995. Total and light-fraction carbon dynamics during four decades after cropping changes. Soil Sci. Soc. Am. J. 59:1398–1403.

Burke, I.C., W.K. Lauenroth, and D.G. Milchunas. 1997. Biogeochemistry of managed grasslands in central North America. p. 85–102. *In* E.A. Paul, K. Paustian, E.T. Elliott, and C.V. Cole (ed.) Soil organic matter in temperate agroecosystems: Long-term experiments in North America, CRC Press, Boca Raton, FL.

Burke, I.C., C.M. Yonker, W.J. Parton, C.V. Cole, K. Flach, and D.S. Schimel. 1989. Texture, climate, and cultivation effects on soil organic matter content in U.S. grassland soils. Soil Sci. Soc. Am. J. 53:800–805.

Burke, I.C., E.T. Elliott, and C.V. Cole. 1995. Influence of macroclimate, landscape position, and management on soil organic matter in agroecosystems. Ecol. Appl. 5:124–131.

Cambardella, C.A., and E.T. Elliott. 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56:777–783.

Campbell, C.A., R.P. Zentner, B.C. Liang, G. Roloff, E.C. Gregorich, and B. Blomert. 2000. Organic c accumulation in soil over 30 years in semiarid southwestern Saskatchewan—Effect of crop rotations and fertilizers. Can. J. Soil Sci. 80:179–192.

Campbell, C.A., and R.P. Zentner. 1993. Soil organic matter as influenced by crop rotations and fertilization. 1993. Soil Sci. Soc. Am. J. 57:1034–1040.

Campbell, C.A., V.O. Biederbeck, R.P. Zentner, and G.P. Lafond. Aug. 1991. Effect of crop rotations and cultural practices on soil organic matter, microbial biomass and respiration in a thin Black Chernozem. Can. J. Soil Sci. 71:363–376.

Davidson, E.A., L.F. Galloway, and M.K. Strand. 1987. Assessing available carbon: Comparison of techniques across selected forest soils. Commun. Soil Sci. Plant Anal. 18:45–64.

Elliott, E.T., I.C. Burke, C.A. Monz, S.D. Frey, K.H. Paustian, H.P. Collins, E.A. Paul, C.A. Cole, R.L. Blevins, W.W. Frye, D.J. Lyon, A.D. Halvorson, D.R. Huggins, R.F. Turco, and M.V. Hickman. 1994. Terrestrial carbon pools: Preliminary data from the Corn Belt and Great Plains Regions. p. 179–194. Defining soil quality for a sustainable environment. SSSA Spec. Publ. No. 35. SSSA, Madison, WI.

Follett, R.F. 2001. Organic carbon pools in grazing land soils. p. 65–86. *In* R.F. Follett et al. (ed.) The potential of U.S. grazing lands to sequester carbon and mitigate the greenhouse effect. CRC Press, Boca Raton, FL.

Franzluebbers, A.J., R.L. Haney, C.W. Honeycutt, H.H. Schomberg, and F.M. Hons. 2000. Flush of carbon dioxide following rewetting of dried soil relates to active organic pools. Soil Sci. Soc. Am. J. 64:613–623.

Franzluebbers, A.J., and M.A. Arshad. 1997. Particulate organic carbon content and potential mineralization as affected by tillage and texture. Soil Sci. Soc. Am. J. 61:1382–1386.

Franzluebbers, A.J., R.L. Haney, F.M. Hons, and D.A. Zuberer. 1996. Determination of microbial biomass and nitrogen mineralization following rewetting of dried soil. Soil Sci. Soc. Am. J. 60:1133–1139.

Gregorich, E.G., and B.H. Ellert. 1993. Light fraction and macroorganic matter in mineral soils: p. 397–407. *In* M.R. Carter (ed.) Soil sampling and methods of analysis. Lewis Publishers, Boca Raton, FL.

Grossmand and Reinsch. 2002. The Solid Phase. Bulk density and linear extensibility. p. 201–228. *In* J.H. Dane and G.C. Topp (ed.) Methods of soil analysis. Part 4. SSSA Book Ser. No. 5. ASA and SSSA, Madison, WI.

Hook, P.B., and I.C. Burke. 2000. Biogeochemistry in a shortgrass landscape: Control by topography, soil texture, and microclimate. Ecology 81(10):2686–2703.

Lal, R., J.M. Kimble, R.F. Follett, and C.V. Cole. (ed.). 1999. Processes governing emissions from the pedosphere. p. 22–30. *In* The potential of U.S. cropland to sequester carbon and mitigate the greenhouse effect. CRC Press, Boca Raton, FL.

Needelman, B.A., M.M. Wander, G.A. Bollero, C.W. Boast, G.K. Sims, and D.G. Bullock. 1999. Interaction of tillage and soil texture: Biologically active soil organic matter in Illinois. Soil Sci. Soc. Am. J. 63:1326–1334.

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. p. 539–594. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. Agron. Mongr. 9. 2nd ed. ASA and SSSA, Madison, WI.

Ortega, R.A., G.A. Peterson, and D.G. Westfall. 2002. Residue accumulation and changes in soil organic matter as affected by cropping intensity in no-till dryland agroecosystems. Agron. J. 94:944–954.

Parton, W.J., J.W.B. Stewart, and C.V. Cole. 1988. Dynamics of C, N, P and S in grassland soils: A model. Biogeochemistry 5:109–131.

Parton, W.J., D.S. Schimel, C.V. Cole, and D.S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci. Soc. Am. J. 51:1173–1179.

Parton, W.J., J.M.O. Scurlock, D.S. Ojima, T.G. Gilmanov, R.L. Scholes, D.S. Schimel, T. Kirchner, J.C. Meanut, T. Seastedt, E. Garcia Moya, A. Kamnalrut, and J.L. Kinyamario. 1993. Observations and modeling of biomass and soil organic matter dynamics for the grasslands biome worldwide. Global Biogeochem. Cycles 7:785–809.

Peterson, G.A., D.G. Westfall, F.B. Peairs, L. Sherrod, D. Poss, K. Larson, D.L. Thompson, and L.R. Ahuja. 1998. Sustainable dryland agroecosystem management. Tech. Bull. TB98–1. Agric. Exp. Stn., Colorado's State Univ., Fort Collins.

Peterson, G.A., A.J. Schlegel, D.L. Tanaka, and O.R. Jones. 1996. Precipitation use efficiency as affected by cropping and tillage systems. J. Prod. Agric. 9:180–186.

Peterson, G.A., D.G. Westfall, and C.V. Cole. 1993. Agroecosystem approach to soil and crop management research. Soil Sci. Soc. Am. J. 57:1354–1360.

Peterson, G.A., D.B. Westfall, L.A. Sherrod, E. McGee, and R. Kolberg. 1991. Crop and soil management in dryland agroecosystems. Tech. Bull. TB91-1 Agric. Exp. Stn., Colorado State Univ., Fort Collins.

Potter, K.N., H.A. Torbert, O.R. Jones, J.E. Matocha, J.E. Morrison, Jr., and P.W. Unger. 1998. Distribution and amount of soil organic C in long-term management systems in Texas. Soil Tillage Res. 47:309–321.

Reeder, J.D., G.E. Schuman, and R.A. Bowman. 1998. Soil C and N changes on conservation reserve program lands in the Central Great Plains. Soil Tillage Res. 47:339–349.

SAS Institute. 1999. SAS/STAT user's guide. Release 7.0 ed. SAS Inst. Inc., Cary, NC.

Scharpenseel, H.W., H.U. Neue, and S. Singer. 1992. Biotransformations in different climate belts; source–sink relationships. p. 91–105. *In* J. Kubat (ed.) Developments in agricultural and managed-forest ecology. Vol. 25. Elsevier Sci. Pub. Co., Amsterdam.

Shaffer, M.J., M. Liwang, and S. Hanson. (ed.). 2001. a review of carbon and nitrogen processes in nine U.S. soil nitrogen dynamics models. p. 55–65. *In* Modeling carbon and nitrogen dynamics for soil management. CRC Press, Boca Raton, FL.

Shaver, T.M., G.A. Peterson, L.R. Ahuja, D.G. Westfall, L.A. Sherrod, and G. Dunn. 2002. Surface soil physical properties after twelve years of dryland no-till management. Soil Sci. Soc. Am. J. 66: 1296–1303.

Shaver, T.M., G.A. Peterson, and L.A. Sherrod. 2003. Cropping intensification in dryland systems improves soil physical properties: Regression relations. Geoderma 116:149–164.

Sherrod, L.A., G. Dunn, G.A. Peterson, and R.L. Kolberg. 2002. Inorganic carbon analysis by modified pressure-calcimeter method. Soil Sci. Soc. Am. J. 66:299–305.

Sherrod, L.A., G.A. Peterson, D.G. Westfall, and L.R. Ahuja. 2003. Cropping intensity enhances soil organic carbon and nitrogen in a no-till agroecosystem. 2003. Soil Sci. Soc. Am. J. 67:1533–1543.

Wander, M.M., and G.A. Bollero. 1999. Soil quality assessment of tillage impacts in Illinois. Soil Sci. Soc. Am. J. 63:961–971.

Wander, M.M., S.J. Traina, B.R. Stinner, and S.E. Peters. 1994. Organic and conventional management effects on biologically active soil organic matter pools. Soil Sci. Soc. Am. J. 58:1130–1139.

Wood, C.W., D.G. Westfall, G.A. Peterson, and I.C. Burke. 1990. Impacts of cropping intensity on carbon and nitrogen mineralization under no-till dryland agroecosystems. Agron. J. 82:1115–1120.

Wood, C.W., D.G. Westfall, and G.A. Peterson. 1991. Soil carbon and nitrogen changes on initiation of no-till cropping systems. Soil Sci. Soc. Am. J. 55:470–476.